J Wood Sci (2004) 50:157–161
DOI 10.1007/s10086-003-0525-y

ORIGINAL ARTICLE

**Subyakto · Toshimitsu Hata · Isamu Ide
Takeshi Yamane · Shuichi Kawai**

Fire protection of a laminated veneer lumber joint by wood carbon phenolic spheres sheeting

Received: November 27, 2002 / Accepted: March 5, 2003

Abstract Laminated veneer lumber joints made with metal plate connectors were protected with wood carbon phenolic spheres (CPS) sheeting and tested for creep under fire. The effects of the carbonizing temperature of charcoal, used as raw material for the CPS sheets, the thickness, and the location of the sheet on the joint regarding the fire-resistance performance of the joint were studied. The time to rupture of the joints covered with CPS sheets made from charcoal carbonized at 800°C (CPS800) was slightly prolonged compared with that of uncovered joints. On the other hand, the time to rupture of CPS sheets made from charcoal carbonized at 1600°C (CPS1600) was markedly extended. The changes in the charcoal properties due to increasing the carbonizing temperature might be the main reason the CPS1600 sheets had higher fire-resistance performance. The thickness and location of CPS1600 sheets have significant effects on the fire resistance of the joint. A highly fire-resistant laminated veneer lumber joint was obtained using a CPS1600 sheet. The CPS1600 sheet with a thickness of 3 mm covering three sides of the joint prolonged the time to rupture 16-fold compared with that of unprotected joints.

Key words Laminated veneer lumber · Joint · Fire protection · Carbon phenolic spheres · Creep test

Introduction

Fire resistance of timber joints has been attracting interest because the joint is considered a weak point in a structure when exposed to fire.[1] Some studies have been conducted to improve the fire performance of timber joints.[2–5] The following are some examples. The fire performance of nailed gusset connections between glue-laminated timbers were improved to more than 1 h of fire protection when the connections were protected with solid wood or gypsum plasterboard.[2] Glue-laminated timber joints with metal joiners covered with mineral boards and ceramic fiber blankets provided excellent fire protection.[3] The fire resistance of laminated veneer lumber (LVL) joints was improved when a drift pin joint with an insert-type steel gusset was applied.[4]

In our previous experiment, the time to rupture of a LVL joint with metal plate connectors protected with graphite phenolic spheres (GPS) sheets was six times longer compared with an unprotected joint,[6] and in our other experiment carbon phenolic spheres (CPS) were developed and anisotropy in thermal properties was clear.[7] A high ratio between horizontal and vertical directions of the molded CPS was observed in regard to thermal properties. These properties could be used for developing a new fire-retardant material for wood composites.[7] The use of materials based on wood charcoal to improve the fire properties of timber joint (especially LVL joints) has not been studied.

The objective of this study was to improve the fire-resistant performance of LVL joints made with metal plate connectors protected with CPS sheeting that were subjected to the creep test under fire. In particular, the effects of the carbonizing temperature of char as a raw material for CPS, the thickness of the CPS sheet, and the location of the CPS sheet overlaid on the joint were evaluated in regard to the fire-resistant performance of LVL joints.

Subyakto
Research Unit for Biomaterials, LIPI, Bogor 16911, Indonesia

T. Hata · S. Kawai (✉)
Research Institute for Sustainable Humanosphere, Kyoto University, Uji, Kyoto 611-0011, Japan
Tel. +81-774-38-3673; Fax +81-774-38-3678
e-mail: skawai@rish.kyoto-u.ac.jp

I. Ide
Lignyte Ltd., Sakai 592-8331, Japan

T. Yamane
Kankyo Techno-Consul, Kobe 651-2273, Japan

Part of this paper was presented at the 4th International Wood Science Symposium, Serpong, Indonesia, September 2002

Materials and methods

Materials and preparations

Wood charcoal was prepared from sugi (*Cryptomeria japonica* D. Don). The wood was carbonized at temperatures of 800° and 1600°C. For the carbonization temperature of 800°C, wood powders were placed in a rotary kiln with a heating rate of 4°C/min and were kept at a constant 800°C for 1h in nitrogen gas. For the carbonization temperature of 1600°C, wood samples were precarbonized at 700°C and used as starting materials. Then they were carbonized in a high-temperature electric furnace (ShinMaywa, Japan) in a nitrogen gas atmosphere at a heating rate of 4°C/min and kept constant at 1600°C for 1h. The chars were cooled to room temperature inside the furnace before being removed. All the chars were sieved with wire mesh screens of 0.5mm to obtain a uniform size of chars.

Carbon phenolic spheres sheets were made by mixing char powder with a phenol-formaldehyde resin and other materials with the composition as follows: char powders/phenol resin/ceramic fiber/organic fiber/poly vinyl acetate 55:20:19:4:2 (% w/w). The CPS sheets were hand-formed and molded with a hot press at 160°C for 1min at a pressure of 2.5MPa. The size of the sheet was 250 × 250 × 1mm, and the density was about 0.41–0.45 g/cm^3. The CPS sheets made from charcoal carbonized at 800°C and 1600°C hereafter are called CPS800 and CPS1600, respectively.

The LVL and metal plate connector (gang nail) used were the same as in the previous experiment.[6] The average density of LVL was 0.59 g/cm^3 and the moisture content 9%. Samples 800mm in length, 38mm in width (flatwise), and 50mm in height (edgewise) were cut into two 400-mm lengths. Metal plate connectors, gang nails of 18-gauge mild steel with a galvanized finish of 79 × 35mm and 1.14mm thick consisting of 20 teeth, were used to connect the LVL butt joint. The metal plate connector consisted of four rows and five columns with 12 long (14.4mm) and 8 short (11.0mm) nails. Two pieces of LVL, each 400mm in length, were joined with two metal plate connectors, one on each side (flatwise). These connectors were pressed manually by a hydraulic press at a pressure of 4.9MPa for about 3s.

The CPS sheet was overlaid on the LVL joint at the metal plate connectors or underneath the joint by hot pressing at 160°C with a pressing time of 1min/mm at a pressure of 200kPa. To ensure good bonding, the sheet was coated with phenol-formaldehyde resin (solid content 50%) in the amount of 70 g/m^2 before being hot-pressed. The sizes of CPS sheet were 50 × 158mm at the sides of the joint or 38 × 158mm at the bottom. The CPS sheets were positioned in three ways: to cover both the sides and the bottom (three sides) of the joint, just the sides (two sides), or just the bottom (one side).[6] Thickness of the CPS sheet was varied at 1, 2, or 3mm. For locations on two sides only, 1-mm-thick CPS sheet was tested.

Creep test under fire

The procedure of creep under fire test was the same as described in previous papers.[6,8] The sample size was 800 × 50 × 38mm. Each sample was set with a span of 750mm. Because the LVL samples were taken from the same lot as in the previous experiment,[6] 10% of the maximum load (i.e., a load of 200N) was applied for each sample. The joint was exposed to fire from a burner with a flame length of 65mm and top flame temperature of 800°–850°C. Thermocouples were inserted into the butt joint to measure the temperature and were connected to a data logger to record the changes in temperature during the test. These thermocouples were located at the inside center in the joint by drilling a small hole at a center point between the metal plate connector and LVL. Deflections of the samples were measured using a dial gauge and recorded manually. The time to rupture was recorded for each sample. Two replications were tested for each condition. Thermograph analysis was also carried out as described in a previous study.[6]

Measurement thermal properties of the CPS sheet

The thermal properties of the CPS sheets (CPS800 and CPS1600) were measured using a laser flash thermal analyzer (Ulvac Shinku-Riko TC-7000, Japan) in accordance with JIS R 1611.[9] Measurements were conducted at room temperature in two directions (i.e., horizontal and vertical). Thermal diffusivity and heat capacity were measured, and thermal conductivity was calculated.

Results and discussion

The effects of the carbonizing temperature of CPS sheet on the fire resistance of LVL joints

Table 1 shows the time to rupture of LVL joints covered with CPS800 and CPS1600 sheets from the creep test under fire (GPS sheet was included as a reference). The times to rupture of the LVL joint covered with CPS sheet were compared with those of uncovered joints (control) and were expressed as a ratio to the control. It was shown that using CPS800 sheets with thicknesses of 1 and 2mm covering the bottom of the joint (one side), the time to rupture was almost the same as that of the control. A slight improvement was obtained when 3-mm-thick sheet was used to cover the bottom of the joint. The CPS800 sheet covering two sides also slightly improved the time to rupture. When the joint was covered on three sides, increased sheet thickness resulted in almost the same time to rupture. Thus, the effect of CPS800 sheets on the fire-resistance performance of LVL joints was not marked.

In contrast, covering the joints with CPS1600 sheets had a marked effect on the fire-resistance performance of LVL joints, as indicated by the significantly extended time to rupture compared with that of the uncovered joint (Table 1). Increasing the thickness of the CPS1600 sheet increased the time to rupture both when the sheets were applied at the

Table 1. Time to rupture of LVL joint covered with CPS800 and CPS1600 sheets

Material	CPS800 sheet		CPS1600 sheet		GPS sheet[a]
	Time to rupture[b] (min)	Ratio to control[c]	Time to rupture[b] (min)	Ratio to control[c]	Ratio to control[c]
One side thickness 1 mm	48.86	1.05	140.08	3.00	3.05
One side thickness 2 mm	50.18	1.08	386.01	8.28	–
One side thickness 3 mm	80.54	1.73	557.87	11.97	–
Two sides thickness 1 mm	74.00	1.59	84.35	1.81	1.89
Three sides thickness 1 mm	77.65	1.67	303.98	6.52	6.56
Three sides thickness 2 mm	78.68	1.69	492.93	10.57	–
Three sides thickness 3 mm	75.73	1.62	756.40	16.22	–

LVL, laminated veneer lumber; CPS, carbon phenolic spheres; GPS, graphite phenolic spheres
[a] Reference values from the previous study[6]
[b] A lower value from two replications of each condition is selected because the two values of each test are mostly very close
[c] The time to rupture of uncovered joint (control) is 46.62 min

bottom of the LVL joint (one side) and on three sides. The location of the sheet on the joint affected the time to rupture. The three sides being covered produced the highest effect, followed by one side (at the bottom), and two sides (at the sides of joint). The increased times to rupture were significant compared to that of uncovered joints. For example, when 1-mm-thick CPS1600 sheet was applied at the bottom, the time to rupture increased 3-fold, whereas with 3-mm-thick sheet it increased almost 12-fold. The largest increase in the time to rupture occurred when three sides were covered with a thickness of 3 mm (i.e., more than 16-fold that of control). If we compared these results with those using GPS sheet as a reference, at the same thickness and position of the sheet on the joint the time to rupture with the CPS1600 sheet were comparable to those of the GPS sheet (Table 1).

Possible reasons why the CPS1600 sheet is more resistance to fire than the CPS800 sheet are thought to be the following. In general, the properties of wood char are affected by the carbonization temperature.[10–13] Particularly, the thermal properties of molded CPS, such as thermal diffusivity and thermal conductivity, increase with increasing carbonizing temperature of the char as raw material in the horizontal direction. In the vertical direction, thermal diffusivity increases but thermal conductivity only slightly increases with increasing carbonization temperature.[7] From the viewpoint of wood charcoal as the raw materials of the CPS sheet, the CPS1600 sheet has higher values of thermal diffusivity and thermal conductivity than does the CPS800 sheet. The results of measuring the thermal properties of CPS sheets showed that the thermal diffusivity and thermal conductivity values for CPS1600 sheets are higher than those of CPS800 sheets (Table 2). With higher thermal property values, the CPS1600 sheet is more resistant to fire than the CPS800 sheet owing to the higher thermal anisotropy ratio of the CPS1600 sheet.

The microstructure of char was changed with increasing carbonization temperature.[12] When charcoal is carbonized at 800°C, its crystalline structure is random. The graphite crystalline structure that layers along the thickness begins to appear at 1300°C with distorted layers; the straightness of the layers gradually improves at 1600°C–1800°C, and the layers finally become stiff and straight at 2100°C.[12] When the crystalline structure is layered randomly (800°C), heat easily penetrates; on the other hand, when it layers along the thickness (1600°C), heat penetration is inhibited. Therefore, CPS1600 sheets that have a graphite-like structure are more resistant to fire than the CPS800 sheets.

Table 2. Thermal properties of CPS sheets

Properties	CPS800 sheet	CPS1600 sheet
Density (g/cm^3)	0.45	0.41
Thermal diffusivity (cm^2/s)		
Vertical	0.0033	0.0046
Horizontal	0.0144	0.0225
Heat capacity (J/g/K)	2.1891	1.7042
Thermal conductivity (W/cm/K)		
Vertical	0.0032	0.0032
Horizontal	0.0142	0.0157

Another fact about the oxygen index values of charcoal when used as the raw material of CPS sheets supports this presumption. The oxygen index is a measure of the resistance of the material to be burned: the larger its value, the more resistance there is to being burned.[14] The index is determined by the oxygen index test. The oxygen index of sugi charcoal carbonized at 800°C is 25, and that of charcoal carbonized at 1600°C is 55.[10] The oxygen index of wood is about 22.[14] Here, when wood was carbonized at 800°C, the oxygen index only slightly increased compared to that of wood; on the other hand, when the wood was carbonized at 1600°C, the index more than doubled. Because the CPS sheets contains 55% charcoal, the CPS800 sheet with the raw material from charcoal carbonized at 800°C was expected to be more flammable than CPS1600 sheet, made from raw material that came from charcoal carbonized at 1600°C.

The carbon content of wood charcoal increases with increasing carbonization temperature.[11] The carbon content (measured with a CHNS/O analyzer) of sugi charcoal carbonized at 800°C is 85.55%, and that of charcoal carbonized

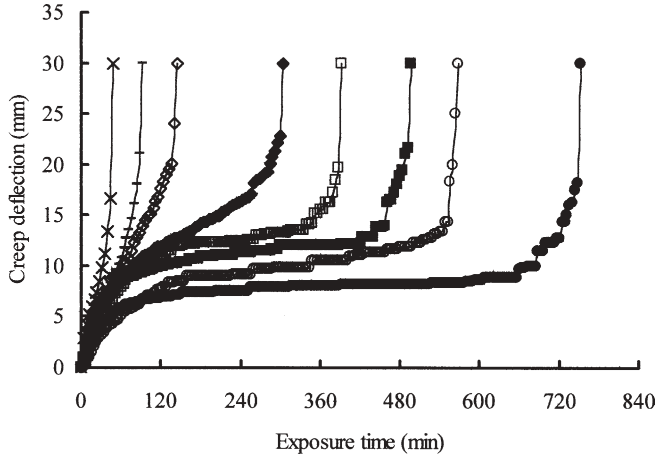


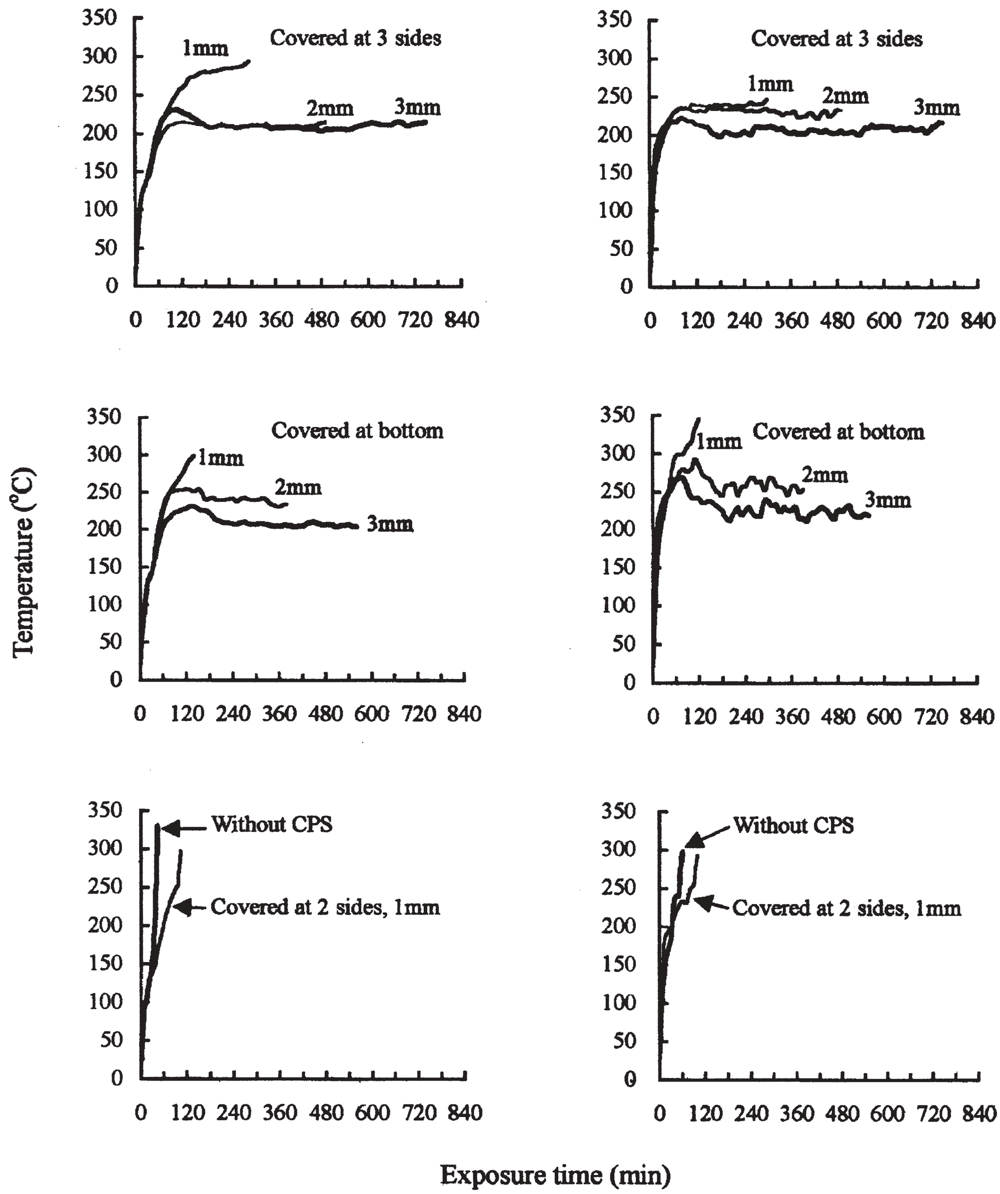
Fig. 1. Creep deflection of laminated veneer lumber (LVL) joints covered with carbon phenolic spheres (CPS) 1600 sheets. *Cross*, control; *minus*, two sides, 1 mm; *open symbols*, one side; *filled symbols*, three sides; *diamonds*, 1 mm; *square*, 2 mm; circles, 3 mm

at 1600°C is 88.60%.[11] The carbon content of wood is 46.4%.[15] In the present experiment it can be assumed that the carbon content of CPS800 sheets is a little less than that of CPS1600 sheets because of the raw materials used.

Deflection of LVL joint covered with CPS1600 sheet exposed to load and fire

Because of the insignificant effect of the CPS800 sheets, further analysis on the effects of thickness and location of CPS sheet was done only on the CPS1600 sheet. The result of creep deflection of LVL joints covered with CPS1600 sheet is presented in Fig. 1. It is shown that the CPS sheet delayed the deflection compared with the control. The effect of the location and thickness of the CPS sheet on creep deflection was highly significant. The uncovered joint burned quickly because the LVL was directly exposed to fire. When only the sides were covered, the deflection

Fig. 2. Temperature rise at the LVL joint during the test as detected by thermocouples. *Left graphs*, at center; *right graphs*, between the metal plate connector and the LVL



became slightly smaller. The least deflection was exhibited when three sides were covered by CPS sheets with the thickness of 3 mm, followed by one side covered with a thickness of 3 mm.

Increasing the sheet thickness decreased the creep deflection. Similar to the observation using GPS sheet,[6] the location of the CPS sheet at the joint affected the deflection of the LVL. When the sheet covered both sides of the joint, the flame directly burned at the bottom part of the joint. Therefore, the deflection occurred rapidly, showing a trend similar to the control (without CPS sheet covering).

Temperature rise of the LVL joint covered with CPS1600 sheet

The temperature rise of LVL joints covered with CPS1600 sheets measured with thermocouples is presented in Fig. 2. The effects of the thickness and location of the sheet are significant in preventing the temperature from rising. At the center in the joint (Fig. 2, left) using 2- and 3-mm-thick sheets, the temperature remained below the critical temperature of 260°C during the test both when the joint was covered on three sides or at the bottom. When 1-mm thick-sheet was used on three sides or at the bottom, the temperature at the center in the joint remained below 260°C for at least 90 min. The temperatures in the center of joints covered on three sides with 1-mm-thick sheet rose higher than those between the metal plate connector and the LVL because a crack gradually developed on the bottom surface of the sheet during the test. Flame then gradually penetrated to the center of the joint, and the temperature rose. Temperatures rose quickly in joints without CPS sheets and in those covered on two sides because the LVL was directly exposed to the flame.

The temperature rise at the center points between the metal plate connectors and the LVL (Fig. 2, right) behaved similar to the temperature at the center in the joint. However, the temperature rose faster than that at the center of the joint at the beginning of the test. With 3-mm-thick CPS1600 sheet covering on the bottom, the temperature remained below 260°C throughout the test.

The results of the thermographic analysis in this study were similar to those found in a previous study.[6] The purpose of the thermographic analysis was to clarify the improvement in the fire performance of the joint covered with CPS sheet by observing the temperature change (transfer of heat) on the surface of the joint in real time. Because the results of the thermographic analysis exhibited a trend similar to that seen in a previous study, the results are not described in this paper.

Conclusions

The fire-resistance properties of laminated veneer lumber joint made with metal plate connectors were improved owing to protection afforded by carbon phenolic spheres sheeting. A maximum time to rupture of 81 min was obtained using CPS800 sheets (joint was covered at the bottom with a thickness of 3 mm), whereas it took 756 min when CPS1600 sheets were used (joint was covered on three sides with a thickness of 3 mm). The time to rupture for the unprotected joint was 47 min. The changes in thermal properties and crystalline structure orientation of charcoal as the raw material of CPS sheets are among the reasons CPS1600 sheets have a higher fire-resistance performance than CPS800 sheets. In this study the CPS sheets were applied to small specimens; if the materials are to be used in a real, practical size, it is necessary to conduct a study on posts and beams.

Acknowledgment This work was supported by the Japan Society for the Promotion of Science through the Ronpaku Program of Subyakto.

References

1. Carling O (1991) Fire behavior of metal connectors in wood structures. In: Proceedings of 1991 international timber engineering conference, London, pp 4.106–4.113
2. Buchanan AH, King AB (1991) Fire performance of gusset connections in glue-laminated timber. Fire Mater J 15:137–143
3. Uesugi S (1993) Fire resistance of glued laminated timber. I. Fire resistance of joint. Mokuzai Gakkaishi 39:58–68
4. Uesugi S, Harada T, Maeda Y, Yamada M (1999) Fire endurance of laminated veneer lumber. Mokuzai Gakkaishi 45:57–61
5. Konig J, Fontana M (2001) The performance of timber connections in fire: test results and rules of Eurocode 5. In: Proceedings of the international RILEM symposium on joints in timber structures, France, pp 639–648
6. Subyakto, Hata T, Ide I, Kawai S (2001) Fire-resistant performance of a laminated veneer lumber joint with metal plate connectors protected with graphite phenolic sphere sheeting. J Wood Sci 47:199–207
7. Subyakto, Hata T, Kawai S, Imamura Y, Ide I (2000) Anisotropic thermal properties of molded carbon phenolic spheres. J Wood Sci 46:16–21
8. Subyakto, Kajimoto T, Hata T, Ishihara S, Kawai S, Getto H (1998) Improving fire retardancy of fast growing wood by coating of fire retardant and surface densification. Fire Mater J 22:207–212
9. JIS R 1611 (1997) Test methods of thermal diffusivity, specific heat capacity, and thermal conductivity for fine ceramics by laser flash method
10. Ishihara S (1996) Carbon composite. In: Salamone JC (ed) Polymeric materials encyclopedia, vol 2C. CRC Press, Boca Raton, pp 957–961
11. Pulido-Novicio L, Hata T, Kurimoto Y, Doi S, Ishihara S, Imamura Y (2001) Adsorption capacities and related characteristics of wood charcoals carbonized using a one-step or two-step process. J Wood Sci 47:48–57
12. Oberlin A (1984) Carbonization and graphitization. Carbon 22:521–541
13. Nishimiya K, Hata T, Imamura Y, Ishihara S (1998) Analysis of chemical structure of wood charcoal by X-ray photoelectron spectroscopy. J Wood Sci 44:56–61
14. LeVan SL (1984) Chemistry of fire retardancy. In: Rowell RM (ed) The chemistry of solid wood. Advances in Chemistry Series No. 207. American Chemical Society, Washington, DC, pp 531–574
15. Shafizadeh F (1984) The chemistry of pyrolysis and combustion. In: Rowell RM (ed) The chemistry of solid wood. Advances in Chemistry Series No. 207. American Chemical Society, Washington, DC, pp 489–529